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Simulations of Inertial Confinement Fusion driven by a Novel Synchrotron Radiation-Based X-Ray Igniter

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Abstract. The advantages and challenges of using a powerful x-ray source for the fast ignition of compressed Inertial Confinement Fusion (ICF) targets have been considered. The requirements for such a source together with the optics to focus the x-rays onto compressed DT cores lead to a conceptual design based on Energy Recovery Linacs (ERLs) and long wigglers to produce x-ray pulses with the appropriate phase space properties. A comparative assessment of the parameters of the igniter system indicates that the technologies for building it, although expensive, are physically achievable. Our x-ray fast ignition (XFI) scheme requires substantially smaller energy for the initiation of nuclear fusion reactions than other methods.

Key words: *Inertial Confinement Fusion, ICF, fusion, Fast Ignition, synchrotron radiation, wiggler, undulator, Energy recovery Linac, ERL, mirror, multiplayer, Compton back-scattering, laser, X-ray phase space, emittance, acceptance*

I. INTRODUCTION

In current work systematic simulations of ignition threshold processes in solid Inertial Confinement Fusion deuterium-tritium (DT) targets have indicated that efficient coupling of ignition energy to a typical compressed target may be realizable using soft x-ray photons in the 2-10 keV range. At these energies virtually all the radiation flux would be absorbed in, say, a solid compressed DT target of diameter ~20 μm and a compressed density of ~600 g/cm^3. The total energy requirement, of the order of 100-1000 Joules, which must be efficiently delivered into the target volume, has led us to consider whether or not the associated phase space requirements could be met with an appropriately designed synchrotron radiation source. In this work we present basic design concepts for an ICF X-ray igniter facility based on moderate-energy (1-2 GeV) Energy Recovery Linacs using photocathode RF guns, ultra-long wigglers, and special X-ray mirrors. The facility, which could attain per-pulse energies of up to several hundred Joules, is shown to be of the same order of scale as the DESY TESLA FEL [1,2] and associated with similar areas of research and development. If constructed, the igniter facility would exceed the per-pulse energy of any existing or proposed synchrotron radiation source by 3-4 orders of magnitude.

We begin by first outlining the background, methodology, and results of our numerical fast ignition studies.

II. FAST IGNITION WITH AN X-RAY SOURCE

In the "Fast Ignition" concept for Inertial Confinement Fusion, which was initially proposed in the work of Tabak et al [3], there are three stages: first, a compressed core of deuterium-tritium with a density compression factor ~1000 is created by conventional means (such as with optical laser beams in direct-drive mode), Second, a follow-on laser beam, at an intensity of ~10^{18} W/cm^2 and a pulse length of 100-300 ps, creates a channel through the underdense blow-off plasma and pushes the critical surface close to the core. In the third phase, a "hole-boring," or "igniter," laser beam with intensity in the (0.5-5) 10^{20} W/cm^2 range and a pulse duration of 5-50 ps penetrates the compressed plasma and generates energetic MeV electrons, sending them into the core. The electron beam ignites the compressed DT and finally the burn spreads rapidly outward resulting in a calculated yield of many times the input energy. In contrast, in more conventional direct or indirect drive schemes the preparation of the dense core and its ignition are not separated and are considered integral parts of one combined process requiring MegaJoules of energy and a highly demanding symmetry of compression. The Fast Ignition concept divides this into several stages with each stage requiring much less energy and easing other constraints.

For detailed and reliable descriptions and numerical evaluations of the fast igniter concept the computer modeling of the relativistic plasma kinetics is definitely required. Initiating the burn with direct laser irradiation requires very high laser fluxes of the order of 10^{21} W/cm^2. Recently performed Particle-in-Cell (PIC) code calculations [4] predict the formation of ultrahigh magnetic and electric fields, the development of strong inhomogeneities, filamentations and electron jets in the focal area, as well as other effects that drastically reduce the efficiency of MeV electron energy deposition into the dense core.

More recently, an alternative Fast Ignition scheme based on the use of laser-accelerated proton beams [5] has been proposed. In this concept, MeV protons are generated and focused from a solid surface close to the (compressed) target using laser irradiation. Due to not so high conversion efficiency of laser energy into the required proton flux, as well as to the relatively large energy spread of the proton beam, large laser energies are required to attain ignition thresholds in DT. Typically, ps laser pulse energy requirements to start ignition in these and other schemes, which have been proposed to date, far exceed tens of kJ.

In our concept a short ps-scale x-ray heating pulse is deposited into a spherical or cone-geometry target which has been compressed to several hundreds grams per cubic cm. As with the other Fast Ignition schemes outlined above such densities are somewhat more straightforward to attain then in the case of conventional isobaric ICF, wherein compressed DT vapors need to be heated up to 5-10 keV in a controlled way to attain the ignition threshold. The higher compressions are more easily attained because they are induced in a "first-stage" process, in which there are fewer constraints on parameters such as initial driver energy and the turbulent mixing of DT and gas. Indeed, these advantages might make it possible to attain even colder and denser cores, with densities well in excess of 600 g/cm^3 [3]. Yet another advantage of our approach is the translucency of the compressed target to x-rays, hence the usual isotropic compression of the ICF target may already be optimal, and more complex configurations such as the cone geometry [6] might not be needed. In the discussion to follow, we will assume that the initial "first-stage" compression has been achieved, either conventionally or by alternative means [7,8], and we will employ the associated known parameters of this compressed state as the initial conditions for our calculations.

In the ignition stage, the dense core absorbs the x-rays almost exclusively by the mechanism of inverse bremsstrahlung. Photoionization absorption is a negligibly minor effect and operates only in the initial stages of x-ray pulse deposition, in the colder layers of the still-compressing spherical target. As soon as the (Z=1) neutrals of the D, T, plastic absorber are photoionized to bare ions this absorption mechanism self-terminates. In some ICF target designs small amounts of mid-Z elements like, for example, Br (A=37) are added [4,6] but they usually do not appreciably screen the dense core against x-rays.

Table 1 shows major characteristic times and scales of parameters for the x-ray Fast Ignition concept. The electron-electron (e-e) collision time - which governs a Maxwellian distribution of electrons upon the absorption of x-ray fluxes of substantial magnitude (~10^{20} W/cm^2) - is extremely short. The quiver energy of electrons in the x-ray fields remains very small (~ 1 eV) so the classical bremsstrahlung mechanism is expected to describe x-ray –target interactions very adequately. The inverse bremsstrahlung absorption coefficient of x-rays is defined (in CGS units) by the expression

$$a_r[cm^{-1}] \sim 8.1\times10^{-37}\,\frac{Z^2 n_e N_i}{\sqrt{kT}\,(h\nu)^3}\left[1-\exp(-h\nu/kT)\right]$$

which includes stimulated emission (here Z is the ion charge, n_e and N_i are the electron and ion densities respectively, and T_e and $h\nu$ are the electron temperature and photon energy in eV), shows that in order for the radiation to be completely absorbed in a minimal volume, and the DT core to satisfy the condition $\rho R > 0.3$-0.5 (where ρ is the mass density and R is the target radius), the absorption coefficient has to lie in the ~1000 cm^{-1} range. This implies that for DT densities of 200-

Table 1.. Time scales of selected processes critical to x-ray fast ignition.

Process	**Characteristic value**	**Comments**
e-e relaxation time	2 10^{-16} s	Being very short, it ensures classical \inv. bremsstrahlung absorption and classical electron thermal diffusion
e-i relaxation time	0.5 ps, at N_e~10^{26}cm^{-3} (400g/cm^3) T_e~5keV)	Ensures fast rates of transfer of energy from electrons to ions. It is shorter than the plasma hydro lifetime
i-i collision time	< 1ps at T~50 keV	Shorter than temperature rise time and dense core plasma lifetime. This ensures fast thermalization of α-particles and classical ion thermal diffusion.
Electron mean free pat to temperature gradient length ratio $\mathbf{l}_e/\mathbf{l}_T$	0.005 at 5 keV, 0.1-0.3 at 40 keV	Close to classical conduction initially up up to 10 keV. Becoming not small enough later on in time when the burn is completely developed
Sound speed	6 10^{-16} cm/s at 5 keV	
Hydro expansion characteristic time	~5-10 ps at core sizes 10-20 µm	Same as in other fast igniter schemes
Characteristic time of T reactions	~3-4 ps at N_e~10^{26}cm^{-3} and T~5keV	Same as in other fast igniter schemes. It must be shorter than hydro expansion time
Heating source energy requirements	500- 1000 J @ (400 g/ cm^3) 200- 400 J @ (800 g/ cm^3)	An order of magnitude less than in Other Fast Ignition schemes

1000 g/cm^{-3}, the x-ray source has to generate photons with energies of the order of 2-10 keV. The electron-ion (e-i) collision time which defines the energy transfer rate from electrons heated by x-ray radiation to the ions remains in the sub-ps range which is favorable for our ignition scheme. Because the electron-ion relaxation time is shorter than both the plasma lifetime and the temperature rise time due to fusion reactions, the radiation pulse will quickly heat the DT ion components to the required minimal initial temperature (>5 keV) at which the reactions start. Numerical simulations using the code RADEX [9] allowed us to evaluate the spectral flux, energy, pulse duration of the x-ray source and other characteristics needed to initiate ignition in compressed DT targets. Fig.1 shows the electron temperature and neutron yield evolution for a DT capsule compressed to 600 g/cm^3 and heated by a 5ps, 1500 J x-ray pulse with wavelength around 2 Å. The pulse energy initially deposited into the 20 μm diameter spot heats the electrons up to a temperature of > 5 keV. Due to the high density and collision rates the ion temperature follows the electron one with only a 5-10% difference, so already just several ps after the start of the x-ray pulse (cf. Fig.1 temperature profile corresponding to 7ps) the electrons are heated back by the ions, which in their turn are being heated by nuclear reactions explosively unfolding inside the hot spot. At ~10 ps the temperature is increased 4-5 times and this happens before the rarefaction wave reaches the center of the hot spot and the plasma starts rapidly expanding and losing density. Modeling reveals that at the same time a very high pressure gradient produces a narrow ~1-2 μm shock front within which the density reach 3 kg/cm^3. Despite its small dimensions this front very effectively stops the escape of α-particles out of the expanding hot spot. Without such a barrier the density in the hot spot after t >12ps would cause ρR to decline substantially

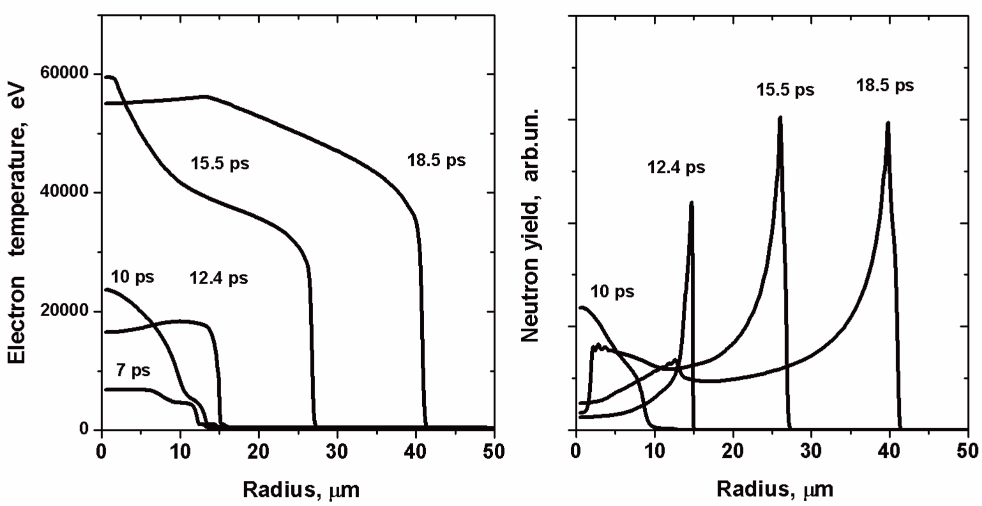

Fig. 1 The family of calculated temperature and neutron yield profiles. The time is marked from the beginning of x-ray source pulse.

below the 0.3-0.5 range needed to contain α-particles inside the hot volume. Due to the fast temperature rise, there are several shock waves bouncing around inside the hot spot between the center and the dense peripheral shock front heating the plasma both in the shock front area and in the center of the hot spot, increasing reaction rates there. The second shock wave going out from the center and formed at substantially higher temperatures at 12-13ps collides with the slower first one causing a jump in local density, temperature, reaction rates and increases by several times the overall speed of expansion (see the very pronounced change in the slope in the R-t curves in Fig.2). The collision produces reflected centered shock wave which causes similar effects in the density, temperature and reaction rates around 15ps in the center of the hot spot (Figs.1 and 2). From t>12-15 ps both the electrons and the much hotter T ions (~1-2 × 10^5 eV) very effectively transfer the heat into a dense shock front area in which the maximum rate of DT reactions takes place, as is clearly seen in the neutron yield curves in Fig.1. Starting from this point on, the burn rapidly spreads further and becomes unstoppable and self-sustaining as ρR permanently increases beyond the ignition threshold.

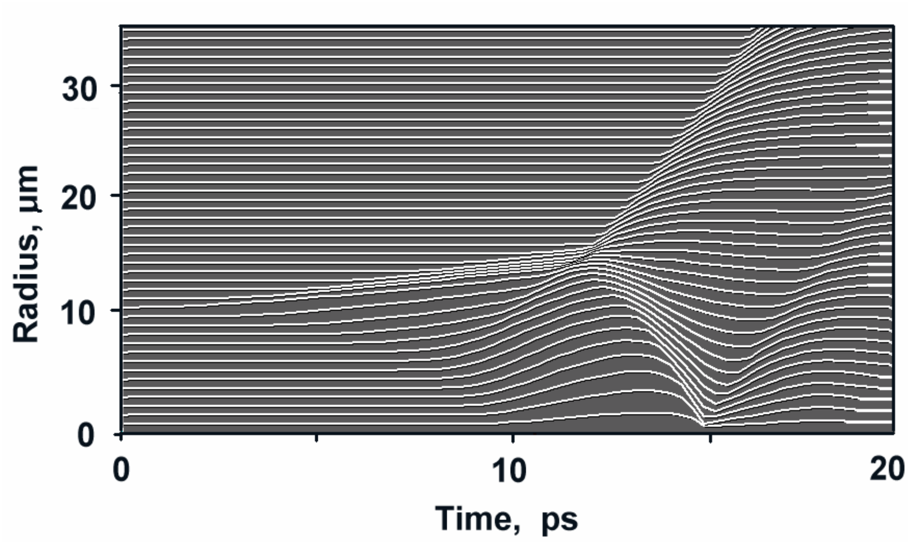

Fig. 2. The r-t diagram for the case shown in Fig.1. Each curve represents the evolution of its (initially equispaced along the R-axis) radius.

III. THE X-RAY SOURCE AND X-RAY OPTICS REQUIREMENTS

The driver for our system, an x-ray source with the required capability of depositing hundreds of Joules into a spherical volume of ~10-20 μm diameter, in an interval of 3-10 ps, does not at present exist, but the technologies for constructing it do [1,2,10-14]. These technologies, based on 1) Energy Recovery Linacs with photocathode RF guns, 2) ultra-long wigglers or undulators (room temperature or superconducting (SC)) and 3) X-ray optics, have within the past decade been used as the basis for X-ray Free Electron Laser (FEL) project designs at both SLAC and DESY, and indeed the latter project features an experimental facility of the same order of scale that we believe the proposed ICF igniter would constitute.

A fundamental advantage of our igniter is that the x-ray source for fast ignition does not have to be coherent or monochromatic like the FEL sources cited above, since even very poor monochromaticity of the spontaneous emission from a suitable wiggler is adequate for this problem. Even more favorably, the spontaneous emission power from a wiggler can be typically 2-3 orders of magnitude or more larger than the power contained in the monochromatic/coherent harmonics of the sources referred to above. The ability to extract the maximum possible power is a critical issue affecting the cost of our concept, since the required x-ray pulse energy is too large to be obtained from one single Linac/wiggler system.

Let us estimate the ratio η of energy radiated by a wiggler, ε_{RB}, to the kinetic energy of the electron bunch, ε_B, and then the number of ERLs needed to attain fast ignition. The kinetic energy of the electron bunch is defined by acceleration electron energy E and charge Q which is equal to current I multiplied by the temporal extent of the bunch, σ_τ , which leads to

$$\varepsilon_B = EI_p\sigma_\tau = EQ_B$$

The energy radiated by the electrons is defined by the Larmor formula (in MKS units) for the radiation by a relativistic electron

$$\varepsilon_{RB} = 6.33 \times 10^{-16} E^2 B^2 L_w \mathrm{I}_P \sigma_\tau = 6.33 \times 10^{-16} E^2 B^2 L_w \mathrm{Q}_B$$

where B is magnetic field and L_w is length of wiggler. From this the η $(= \varepsilon_{RB} / \varepsilon_B)$ is

$$\eta \cong 6.33 \times 10^{-16} E\, B^2\, L_w$$

The electron energy for a transverse wiggler with a magnetic field B to radiate a spectrum with a critical energy ε_c, in practical units, is

$$E[GeV] = 1.23\sqrt{\frac{\varepsilon_c[keV]}{B[T]}}$$

and hence

$$\eta = 7.81 \times 10^{-7}\sqrt{\varepsilon_c B^3}\, L_w$$

which leads to the number N of ERLs required to produce the number of x-ray Joules, E_{IG}, needed for ignition in terms of ERL and wiggler parameters:

$$N = \frac{E_{IG}[J]}{\eta E[GeV] Q_B[nC]} \cong \frac{E_{IG}[J]}{\varepsilon_c[keV]\, B[T]\, L_w[km]\, Q_B[\mu C]}$$

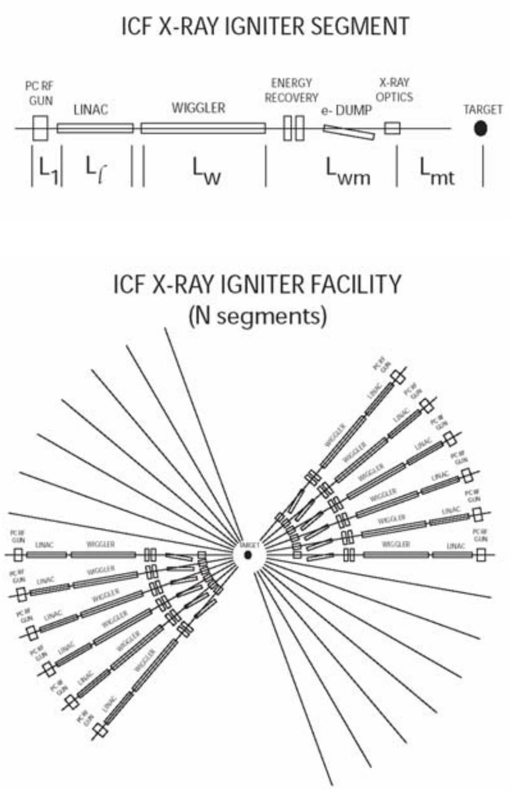

Fig. 3. ICF X-ray Ignition Facility layout based on a radially symmetric array of synchronized ERL / wiggler sources ("segments"). In actual operation selected groups of Linacs could be deactivated to allow anisotropic (broadside) irradiation of selected target geometries.

Taking ε_c at ~5keV and assuming a wiggler field of ~3-5T, it is seen that ERLs with E~1.2-1.5 GeV would be needed. With optimal technology η could be in the range of several percent, and assuming that roughly 50% of the wiggler spectrum could be used to efficiently heat the ICF target, a rough estimate of practical (or somewhat enhanced) Linac, photocathode RF gun, and wiggler parameters [10,15,16] yields ~1 useable Joule/ERL. Hence, to get the needed energy, on the order of 100 ERLs would have to be multiplexed and arranged in a synchronized configuration (see Fig. 3).

The igniter's x-ray optics will need to collect hundreds of Joules in a several ps pulse and focus them into a ~20 μm spot. Fortunately, techniques based on extreme grazing incidence or multiplayer mirrors are well developed and used extensively at both synchrotron radiation (SR) installations and in astronomy [13,14]. Nonetheless, due to the extreme length of the wigglers and their relatively large opening angle (~K/γ) the scale of the mirrors for the X-ray Igniter will be up to an order of magnitude larger than typical at most SR facilities. It is anticipated that special techniques or configurations (e. g., segmented-mirror arrays or segmented/offset wiggler arrays) may need to be developed to most effectively couple the radiation from the wigglers - which might itself be partially screened by the wiggler structure - to the target.

Table 2 summarizes the current and projected parameter ranges of the technologies associated with the x-ray source indicating that many of them are very close to the state of current art or to parameters under contemporary research and development. The anticipated cost for this source is high, even assuming an optimistic cost of ~$15/25M /ERL. Clearly, further minimization of the cost will be desirable for the source to become practical for fusion applications.

Table 2.. Current and projected parameters of selected technologies critical to the x-ray fast igniter facility.

	current	**projected**
Q_B[μC]	0.1 - 0.01	0.1-0.01
E [GeV]	1-10	1-10
B[T]	2-6	2-6 (conventional/SC)
L_w[km]	0.1-0.33	0.5-1.0
E_{IG}[J]	100 (minimum)	?
ε_c[keV]	3-6	3-10
L_{f_1} [m]	100-300	100 (SC) - 500
X-ray Optics Aperture [m]	<1	~2-10

IV. SUMMARY

We can point out several significant advantages of the x-ray fast igniter approach.

- Almost complete utilization of the x-ray source energy delivered to the 10-30 μm size target volume and hence the smallest total energy (wall plug-to-radiation) requirements for ignition.
- The required photon energies lie in the well understood and technologically supported 2-10 keV not the MeV, range.
- Tunable source wavelength allows the matching of the focal spot size and absorption depth important to minimize energy requirements.
- Transparency of blow-off corona and debris to x-ray radiation. Virtually all of the radiation is absorbed in the dense core.
- Essentially classical physics of interaction of x-rays with the dense DT core, which simplifies numerical studies and increases the reliability of predictions. The higher (by 3-4 orders of magnitude) photon energy of the x-ray source compared to optical lasers practically eliminates hot electrons, self-focusing, filamentation and many deleterious turbulent and nonlinear phenomena.
- Due to the use of ERL technology, the gross energy budget of even several hundred ERL/wiggler igniter segments is estimated to be at about only a few percent to the gross target energy yield on a per-shot basis.
- Contemporary projects already exist (e.g., the TESLA FEL) that involve identical or similar source and optics technologies and are of a similar magnitude of scale.
- The research and development required to fully optimize the x-ray igniter and substantially reduce its cost requires less-than-one-order-of-magnitude advancements in only a few of the parameters of the underlying technologies.

The results of this initial investigation of the x-ray Fast Ignition scheme, which in general appear promising, also indicate that broader and more detailed research in certain areas is needed. The physics of absorption, burn and expansion can be further refined together with further optimization of x-ray source characteristics. Possibly other new ideas and different methods for x-ray generation may appear in the future. The development of optimal large-scale X-ray mirrors based either on extreme grazing incidence or variable-band multilayer techniques [12], or possibly new kinds of optics altogether constitutes a challenging area of physics and engineering research and development. Continuing applied physics and engineering research in improving LINACs with pc RF guns toward extracting higher-charge bunches at substantially lower cost and in optimizing ultra-long wiggler designs (room temperature or SC) to maximize the extraction of x-ray photons, can further reduce the overall igniter cost, which would be important for designing initial proof-of-principle experiments. One of the straightforward ways for doing is identical to that proposed for other Fast Ignition schemes [3,5], i.e., to increase the fuel compression (and thereby density) with an associated reduction of focal spot size (and hence the amount of mass to be heated) to keep the ρR condition valid. For this it will also be necessary to correspondingly shorten the x-ray pulse duration and provide tighter focusing of the x-rays with grazing incidence optics. To illustrate, Fig.3 shows the pulse energy requirements vs. compression for the X-ray Fast Ignition (XFI) vs. Proton Beam FI scheme [5]. The resulting reduction of the ignition threshold by more than an order of magnitude looks promising for the practical realizability of the x-ray based Fast Ignition concept.

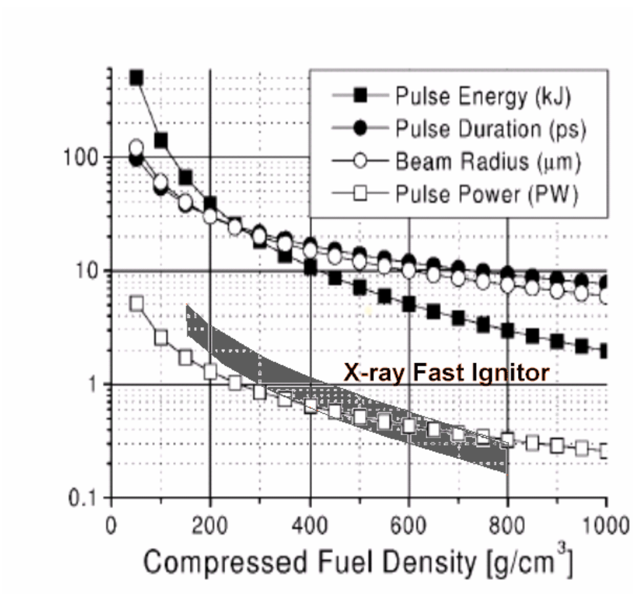

Figure 3 Comparison of pulse energy requirements (in kJ) for the x-ray Fast Ignition scheme (black band curve) with energy requirements using the proton beam approach (solid squares) [5,17].

We conclude by pointing out that one noteworthy aspect of our investigation has been that in the past few decades' push toward "4th Generation" sources [18], the "10-fold or more" increase in the total energy within a single photon pulse has been the one phase space parameter that has heretofore received little or no attention. If developed, the proposed x-ray ICF ignition facility would constitute an entirely new 4th Generation x-ray source of this type.

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